

ANALYSIS OF BEAM LOSS MECHANISM IN THE PROJECT-X LINAC.*

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Abstract

Minimization of the beam losses in a multi-MW H⁻ linac such as ProjectX to a level below 1 W/m is a challenging task. The impact of different mechanism of beam stripping, including stripping in electric and magnetic fields, residual gas, blackbody radiation and intrabeam stripping, is analyzed. Other sources of beam losses are misalignments of beamline elements and errors in RF fields and phases. We present in this paper requirements for dynamic errors and correction schemes to keep beam losses under control.

INTRODUCTION

Beam losses in a high power linac need to be minimized in order to allow “hands-on maintenance” on the accelerator. This requirement implies an activation limit below 100 mrem/hr at 30 cm from the component surface, after extended operation of the machine (~ 100 days) and four hours of down time [1]. Simulations and measurements for operating facilities such as the Los Alamos Neutron Science Center (LANSCE) 800 MeV proton and H⁻ linac and Proton Accumulator Ring indicate this criterion corresponds to a beam power loss of about 1 W/m or less for energies above 100 MeV. For lower energies, higher losses may be tolerated since the activation is less effective.

Uncontrolled beam losses such as arising from misalignment of accelerator components, rf phase and amplitude jitter, beam halo or beam mismatch need to be carefully studied during the design of a high-power linac to ensure its robustness to the loss requirement of 1 W/m. Another potential source of beam loss in a H⁻ linac concerns the ionization of the H⁻ ions. In fact, as the H⁻ ions travel along the linac they are subject to blackbody radiation, electromagnetic fields (Lorentz stripping), collisions with the residual gas molecules and intrabeam forces (intrabeam stripping). Any one of these four effects may result in the stripping of the loosely bound electron (0.75 eV) of the H⁻ ion, which in turn produces activation through the loss of neutral hydrogen atoms.

This paper presents beam loss estimates along the 3 GeV CW Superconducting (SC) linac currently under development at FNAL. The impact on the beam dynamics of accelerator component misalignments and rf phase and amplitude jitter is studied with the ANL code TRACK [2] and CEA code TRACEWIN [3]. An estimate of the losses from the four above-mentioned stripping mechanisms is presented.

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THE FNAL 3 GEV CW LINAC

A layout of the present configuration of the linac is shown in Figure 1 and detailed in [4]. The linac is designed to deliver an average current of 1 mA (chopped peak current of 10 mA) which at 3 GeV produces a beam power of 3 MW. The total length of the linac in its current version is ~ 445 meters.

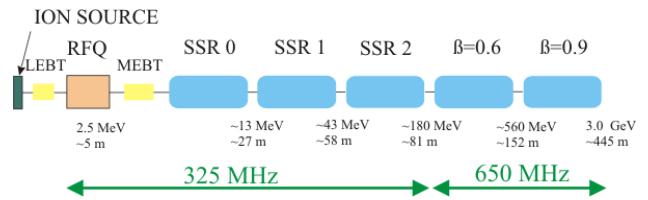


Figure 1: Layout of the FNAL 3 GeV CW SC Linac

The injector consists of an H⁻ ion source followed by a radio-frequency quadrupole (RFQ) and a Medium Energy Beam Transport (MEBT) that matches the 2.5 MeV beam into the SC linear accelerator. In order to efficiently accelerate the beam from 2.5 MeV to 180 MeV, three different types of Single Spoke Resonators (SSR 0, SSR 1 and SSR 2) operating at 325 MHz are foreseen, as depicted in Figure 1. Further acceleration to 3 GeV is achieved using two types of 5-cells elliptical cavities ($\beta = 0.6$ and $\beta = 0.9$) operating at 650 MHz. In the 325 MHz section, focusing is done with 5 T superconducting solenoids located inside the cryomodules. The current version of the linac foresees as focusing elements in the 650 MHz section quadrupole doublets located between the cryomodules.

ERRORS AND CORRECTORS

The impact on the current lattice of static transverse misalignment errors of accelerator components (solenoids, quads and cavities) and dynamic RF jitter (field and amplitude) have been studied on the FermiGrid with the code TRACK. A summary of the results is presented in Table 1. The transverse misalignments δ_{xy} are setup in the code such that the element ends are randomly misaligned (uniform distribution) horizontally and vertically by the same value which does not exceed the maximum input δ_{xy} . Concerning the dynamic RF errors, TRACK generates Gaussian distributions truncated at 3σ .

Reported in Table 1 are the error type of each element of the beamline, the error value and the total beam fraction lost at the end of the linac. For each set of errors, 400 randomly generated error runs were performed with TRACK using $5 \cdot 10^4$ macroparticles per run. For solenoid misalignments $\delta_{xy} > 300 \mu\text{m}$, beam losses surpassing 1 W/m are

Elt	Error Type	Error Value	Fraction lost
Sol.	δ_{xy}	150 μm	$3.5 \cdot 10^{-5} \%$
Sol.	δ_{xy}	300 μm	0.4 %
Sol.	δ_{xy}	500 μm	9 %
Sol.	δ_{xy}	750 μm	38 %
Sol.	δ_{xy}	1000 μm	69 %
Quad.	δ_{xy}	150 μm	0 %
Quad.	δ_{xy}	300 μm	0 %
Quad.	δ_{xy}	500 μm	0 %
Quad.	δ_{xy}	750 μm	4 %
Quad.	δ_{xy}	1000 μm	22 %
Cav.	$\delta_\phi + \delta_E$	$0.5^\circ + 0.5\%$	0 %
Cav.	$\delta_\phi + \delta_E$	$1.0^\circ + 1.0\%$	$5 \cdot 10^{-6} \%$
Cav.	$\delta_\phi + \delta_E$	$1.5^\circ + 1.5\%$	0.04 %
Cav.	$\delta_\phi + \delta_E$	$2.0^\circ + 2.0\%$	0.9 %
Cav.	$\delta_\phi + \delta_E$	$2.5^\circ + 2.5\%$	3.6 %

Table 1: Impact on the total beam fraction lost at the end of the linac of element misalignment errors and RF field jitter. From TRACK.

predicted by the code mainly at the frequency transition. The same observation is made with quadrupole misalignments $\delta_{xy} > 750 \mu\text{m}$ with losses evenly spread on the entire 650 MHz section of the linac. The study of the dynamic phase and amplitude field jitter taken separately showed that no losses are predicted respectively for $\delta_\phi = 1.5^\circ$ and $\delta_E = 1.5\%$ and losses below the 1 W/m limit predicted for respectively $\delta_\phi = 2^\circ$ and $\delta_E = 2\%$. Combined as reported in Table 1, TRACK predicts no losses at $1.0^\circ + 1.0\%$ and losses higher than 1 W/m for $1.5^\circ + 1.5\%$. Figure 2 reports the maximum and average losses along the linac for this last configuration as predicted by TRACK and TRACEWIN. For TRACEWIN simulations, 100 runs were performed using $3 \cdot 10^4$ macroparticles per run. Noteworthy is the good agreement between the two codes which both predict high losses at the transition between the two set of 650 MHz cavities ($\sim 150 \text{ m}$).

The impact of the roll of the quads around the z axis, the dynamic field jitter of the quads and solenoids and the transverse misalignments δ_{xy} of the cavities was also studied with TRACK in the same configuration as previously mentioned (400 seeds). These three error types have a marginal impact on the beam dynamic for values respectively of 5 mrad, 1% and $\delta_{xy} = 1 \text{ mm}$.

The TRACK correction algorithm aims to steer the beam so that the transverse displacements measured by the BPM's are minimized. Figure 3 shows TRACK simulations of the corrected / uncorrected horizontal beam centroid motion taking $\delta_{xy} = 1 \text{ mm}$ for all the elements of the beamline (solenoids, cavities, quadrupoles), RF field dynamic jitter of $1.0^\circ + 1.0\%$ and quad rolls of 5 mrad. In this correction scheme, 1 corrector and 1 monitor per solenoid and per quadrupole doublet were assumed. The resolution and the offset in position of the BPM's are respectively $30 \mu\text{m}$ and 1 mm . As presented in Figure 3, before correction the horizontal beam centroid growths along the linac to reach an

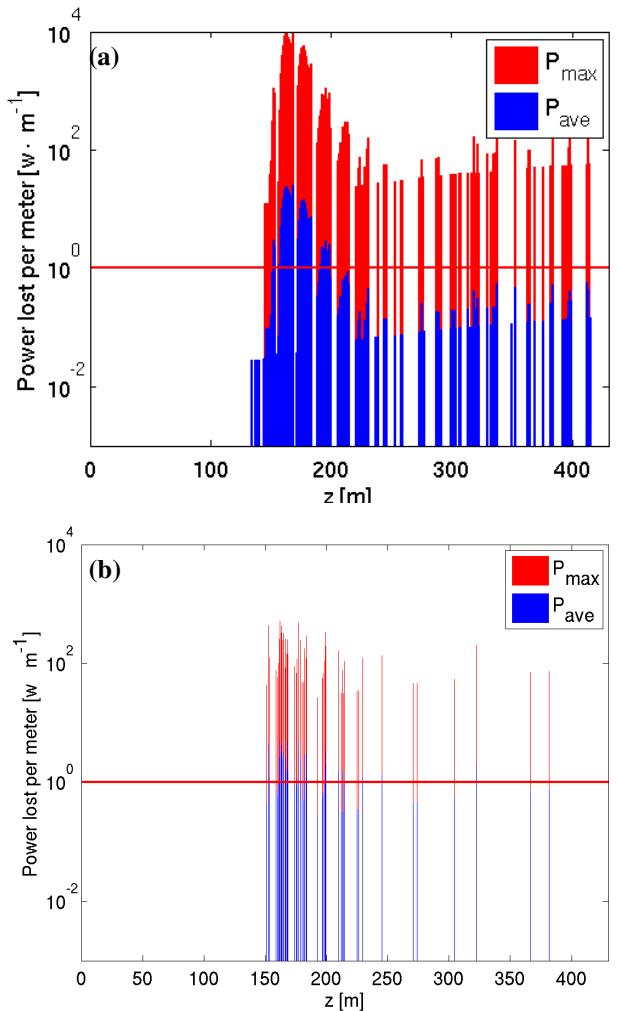


Figure 2: (a) TRACK and (b) TRACEWIN simulations of the maximum and average loss pattern along the linac operating at 3 MW for RF field dynamic errors of $1.5^\circ + 1.5\%$. The red bar represents the 1 W/m limit.

amplitude $\pm 50 \text{ mm}$ and losses much higher than 100 W/m are predicted by the code in several locations along the linac. After correction, the horizontal beam centroid motion keeps below 3 mm and no losses due to element misalignments and RF field jitter are observed.

Based on this study and following a more conservative approach, the requirement for solenoids, quadrupoles and cavities misalignments is $\delta_{xy} = 500 \mu\text{m}$ and $1.0^\circ + 1.0\%$ for RF dynamic field jitter. The requirement on the resolution and on the offset in position of the BPM's are respectively $30 \mu\text{m}$ and $500 \mu\text{m}$.

H⁻ STRIPPING LOSSES

Four mechanisms are currently known as capable of stripping the H⁻ ions during their transport along the linac leading to uncontrolled beam loss. These mechanisms are: (i) the interaction of the H⁻ ions with the residual gas or (ii)

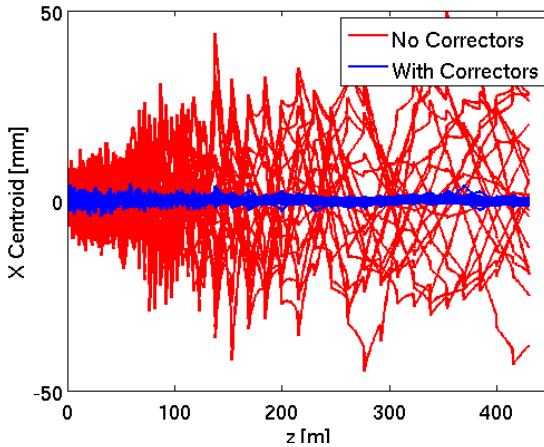


Figure 3: TRACK simulations of corrected / uncorrected horizontal beam centroid motion along the linac for the set of errors $\delta_{xy} = 1$ mm (solenoids, cavities, quadrupoles), $1.0^\circ + 1.0\%$ (dynamic RF field jitter) and quad roll of 5 mrad around the z-axis. 1 corrector and 1 monitor were used per solenoid and per quadrupole doublet.

with the electromagnetic fields, (iii) the blackbody radiation and (iv) the intrabeam stripping. This last mechanism has been described in [5] and it has been recently implemented in TRACK [6].

Figure 4(a) shows the predicted beam losses from the four aforementioned stripping mechanisms as simulated with TRACK. These losses represent an average over 500 runs performed on the FermiGrid with 10^6 macroparticles per run. The warm sections of the linac (inter-cryomodule spacing) were set at 300 K in the code with a vacuum composition of 70% H₂, 10% H₂O, 10% O₂ and 10% CO and a pressure of 10^{-7} torr. Concerning the cryomodules, a temperature of 2 K was used with 100% H₂ and 10^{-10} torr. It can be noticed from Figure 4(a) that in these conditions the stripping losses contribute to a general background below 0.1 W/m with some peaks reaching the 1 W/m limit. The main contributor to the background are the losses from the intrabeam stripping. The observed peak are the contribution from the residual gas in the inter-cryomodules spacing, as depicted in Figure 4(b) which concerns only stripping from this effect. Keeping the vacuum below 10^{-8} torr would reduce these peaks by one order of magnitude, i.e. below 0.1 W/m. Stripping from blackbody or electromagnetic fields are not a concern for the current design.

CONCLUSION

With the proper correction scheme, the present lattice shows no losses for realistic element misalignments (solenoids, quadrupoles and cavities up to $\delta_{xy} = 1$ mm) and RF field jitter (phase and amplitude up to $1.0^\circ + 1.0\%$). Also with a vacuum at or below 10^{-8} torr at 300 K, stripping losses should remain below 0.1 W/m. The next step in our simulations is to study the behaviour of this lattice

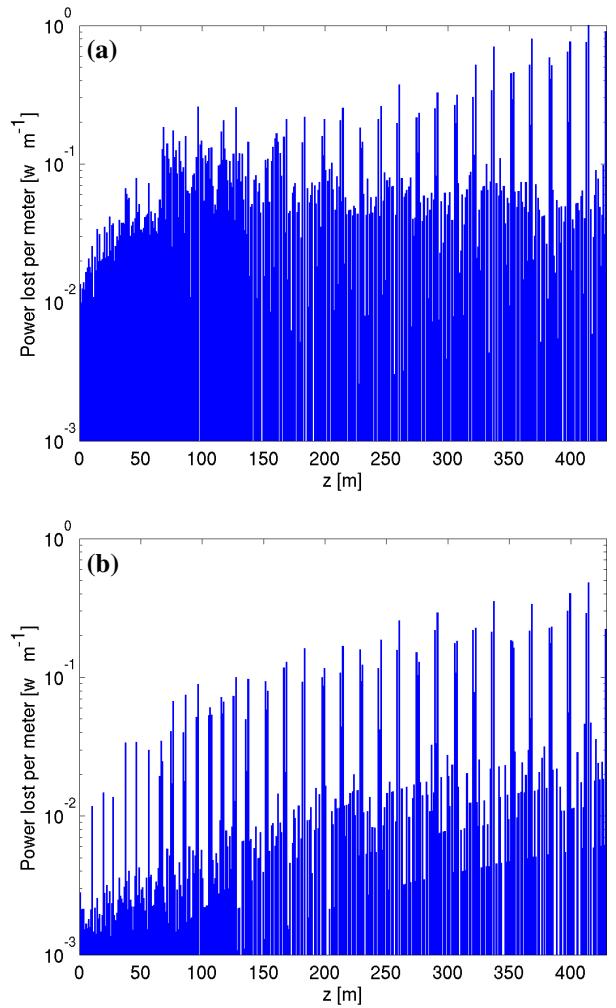


Figure 4: TRACK simulations of the beam power lost per meter from (a) intrabeam, blackbody, residual gas and lorentz stripping and (b) only residual gas along the FNAL linac operating at 3 MW.

with respect to beam mismatch coming for instance from the input distribution and/or the cavity field limitations .

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